The Processes in the Electromagnetic Exciter of Low-Frequency Oscillations in its Functioning Mode

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Abstract: This research is devoted to the peculiarities of the processes in the Electromagnetic Exciter of Low-Frequency Oscillations (EME LFO) and to the modeling and simulation of physical subsystems. In terms of simplicity of its design and implementation schemes choosing EME LFO as the base unit of vibration alternator's function module is quite reasonable and promising and provides opportunities to develop EME LFO operating in generator mode with the view of its practical use as a universal highly effective tool for converting mechanical energy of natural origin such as moderate and weak wind flows and water flow in the rivers. Consideration of the processes in the Electromagnetic Exciter of Low-Frequency Oscillations (EME LFO) and theoretical propositions forms the basis for the practical implementation of a whole class of original design solutions built on its base with a new demanded quality of generator mode of its functioning.

Key words: Electric magnet, resonant frequency, tractive effort, subsystem, flux, gap distance, harmonic composition

INTRODUCTION

In terms of simplicity of its design and implementation schemes choosing Electromagnetic Exciter of Low-Frequency Oscillations (EME LFO) as the base unit of vibration alternator's function module is quite reasonable and promising and provides opportunities to develop EME LFO operating in generator mode with the view of its practical use as a universal highly effective tool for converting mechanical energy of natural origin such as moderate and weak wind flows and water flow in the rivers.

Consideration of the peculiarities of the processes in the Electromagnetic Exciter of Low-Frequency Oscillations (EME LFO) and theoretical propositions forms the basis for the practical implementation of a whole class of original design solutions built on its base with a new demanded quality of generator mode of its functioning.

In the researches of researchers (Nitusov, 1958; Komarov, 1974; Kuliev, 1981; Siebert, 1985; Melkina, 1982; Smirnova, 1983; Tumanov, 2001), it is shown the principal capabilities of the circuit of electromagnetic exciter of low-frequency mechanical oscillations with series capacitor in relation to the creation of devices with vibro effect as vibration engines for different technological processes. In these researches, there are also specified conditions which must be satisfied by applied in this case vibration exciters and it is the realization of these conditions that predetermines the success of the functioning of the entire vibration device as a whole. Presented in the annotation formulation of the task of the research shows that there are some difficulties in the designing of the above devices as determined by the lack of sufficiently expanded theory of their functioning. Therefore, it is required to clarify a number of theoretical propositions in relation to the considered type of electromagnetic exciters of low-frequency mechanical oscillations for the purpose of further, development of these propositions, the above is the content of subsections of this study.

ELECTROMAGNETIC EXCITER OF LOW-FREQUENCY MECHANICAL OSCILLATIONS WITH SERIES CAPACITOR MAIN DEPENDENCIES

Electromagnetic exciter of low-frequency oscillations is a system: "AC electromagnet with series capacitor." Structurally, it is shown in Fig. 1. Functioning feature is that there are many variables that become factors that determine non-sinusoidal working processes under

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Fig. 1: Electromagnetic exciter of low-frequency oscillations structure

sinusoidal power. Since, taking into account all the features of variables is difficult and in some cases not reasonable, we choose from the entire set of these factors the basic factors and note their features.

For this purpose, first and foremost form the equation system (which hereinafter will enable to obtain the mathematical model) proceeding from the presence of three physically dissimilar subsystems (Katsubinski, 1977) of the vibro-exciter design: electric, magnetic and mechanical (Fig. 2).

According to Katsubinski (1977) electromagnet may be substituted by a Chain-Theoretic Model (CTM, Fig. 2) containing the above cascaded subsystems in the form of electric circuits (by analogy), interconnected by ideal transformer (in the section of electromagnetic energy conversion) and gyrator (in the section of magnetomechanical energy conversion). This representation is convenient as it enables to specify the conditions: identify the main factors and discard the secondary.

Consequently, the above system must include three equations for these physical subsystems. They are: a) For the electric subsystem (Fig. 2):

$$U_{ab} + U_{bd} + U_{dg} - U = 0 \qquad (1)$$

Where:
U = U_{ag}
U_{ab} = $U_{ab} \times i$
U_{bd} = $w \, d\Phi/dt$
U_{dg} = $1/c \int i dt$ voltage in the CTM sections
Φ = Magnetic flux in the electromagnet coil

Fig. 2: Chain-theoretic model

i = Current in the circuit of the electromagnet coil
r, c = Active resistance and capacitance
w = The number of windings of the magnet

b) For magnetic subsystem:

$$U_{\mu} = \Phi \times R_{\mu\Sigma} \left(R_{\delta'} + R_{\delta''} + R_{steel} \right) \qquad (2)$$

Or:

$$iw = \Phi \times \left(\frac{\delta'}{\mu_0} + \frac{\delta''}{\mu_0} + \frac{l_{steel}}{\mu_{steel}} \right) \times \frac{1}{S_{\mu}}$$

Where:
δ = Air gap in the magnetic system of traction electromagnet of the EME LFO
δ', δ'' = Air gaps under the first and the second poles, respectively
S_{μ} = The area of the ends of the electromagnet's core, directed towards the movable armature
R_{δ} = Magnetic resistance of the air gaps
R_{steel} = Magnetic resistance in the steel of the magnetic conductor of the EME LFO including the core and the armature of the electromagnet
μ_0 = Constant magnetic conductivity
μ = Magnetic conductivity (constant) of the steel
$U_u = iw$ = Magnetizing force of the electromagnet coil

Note that the requirements for the constructional implementation of the EME LFO regarding its core and the armature and the conditions of their functioning are defined as follows: $\delta' = \delta'' = \delta$ and $\mu_{steel} > > \mu_0$. In addition in the further, theoretical studies we will take: $s_{\mu}' = s_{\mu}' = s_{\mu}$. Then, Eq. 2 takes the form:

$$iw = \Phi \times \left(\frac{1}{\mu} \times \frac{2\delta}{S_{\mu}} \right) \qquad (3)$$

c) For the mechanical subsystem:

$$F_{im} + F_{fric} + F_{sping} = F\Sigma^{(t)} \qquad (4)$$

Where:

$$F_{im} = m_\Sigma \frac{d^2 x}{dt^2}, \quad F_{fric} = R_{mech} \frac{dx}{dt},$$

$$F_{spring} = k\Sigma x\text{-force efforts in the CTM}$$

Where:

x   =   Armature's shift (Fig. 1)

m_Σ =   The total mass of the moving parts

k_Σ =   Stiffness of elastic elements

$F_\Sigma(t)$ =   Tractive effort exerted by the magnetic system

In this equation, tractive effort's value is expressed by the relation in accordance with Maxwell's formula:

$$F_\Sigma(t) = \frac{1}{2\mu_0} \times \frac{1}{S_\Sigma} \times \Phi_\Sigma^2(t)$$

Where:

$\Phi_\Sigma(t)$ = The value of the magnetic flux in the air gaps, determining tractive effort

$S_{\mu\Sigma}$ = $s'_\mu + s''_\mu$ total traction area of the poles $\left(s'_\mu = s''_\mu = s_\mu, S_\Sigma = 2s_\mu \right)$

Natural frequency of the mechanical part of the system is determined in accordance with:

$$f_v = \frac{1}{2\pi} - \sqrt{\frac{k'_\Sigma}{m_\Sigma}}$$

Given the above, represent the equations of the subsystems in a single system of equations:

$$r \times i + w\frac{d\Phi}{dt} + \frac{1}{c}\int idt = U_{cemu}, \tag{5}$$

$$iw = \Phi \frac{1}{\mu_0} \frac{\delta}{S_\mu} \tag{6}$$

$$m_\Sigma \frac{d^2}{dt^2} x + R_{Mex} \frac{dx}{dt} + k'_\Sigma x = \frac{1}{2\mu_0} \times \frac{1}{S_\Sigma} \Phi_{(\delta)}^2 \tag{7}$$

Note, however that the presented recording does not form a system of equations in the mathematical sense for the following reasons.

First, consider that the magnetic flux in the coil "Φ" is connected with the magnetic flux in the gap "$\Phi_{(\delta)}$" by the following relation:

$$\Phi = \Phi_{(\delta)} + \Phi_{stray} \tag{8}$$

where, Φ_{stray} stray flux in the gap and in the space between the poles of the yoke. Stray flux is generally not small and can be (Kuliev, 1981):

$$\Phi_{stray} = (0.1 \div 0.3)\Phi \tag{9}$$

However, its significant share is in the space between the planes of the core, extending outside the frame of the winding but remote from the movable armature. Therefore, shared value of the Φ_{stray} from the value of the Φ can be taken as independent of the armature movement and allowed for by the introduction of the constant coefficient K_{stray}, i.e.:

$$\Phi_{stray} = K_{stray}\Phi$$

Therefore:

$$\Phi_{(\delta)} = \left(1 - K_{stray}\right)\Phi$$

and under the assumptions taken above $K_{stray} = (0.1 \div 0.3)$ in the case $K_{stray} = 0.2 \ \Phi_{(\delta)} = 0.8\Phi$, i.e.:

$$\Phi_{(\delta)} = K_{stray}\Phi \tag{10}$$

where, $K_{stray\_av.} = 0.8$. The above arguments are forcing to take into account that the variables inserted into the presented equations are unequal in the various subsystems, giving the number of unknowns larger than the number of equations. Given this, we compare the unknowns occurring in these equations to simultaneously reduce their total number (and consequently, the number of equations).

Referring to the equation for the magnetic subsystem, note that a member of its right side, the magnetic flux is recalculated by using a section of the air gap (δ, S_μ). And, therefore, it is the magnetic flux $\Phi_{(\delta)}$. However in the left side of this equation parameters of the winding w are being used. Since in the further, analysis for the comparability of the results of the experiment with the calculated data it is reasonable in the equation for the electrical subsystem to operate with the full value of the current i, then the equation for the magnetic subsystem should use the same value of the current. Then to eliminate inconsistencies in the variables Eq. 5-7 we use Eq. 10 which allows us to reduce all three equations to one variable relatively to the magnetic flux "Φ".

However, there are two other variables not allowing to reduce Eq. 5-7 to a closed system of equations without the introduction of an additional bond. These are the value of the air gap δ and the value of armature's shift x (Fig. 1):

$$\delta_0 = \delta + x \tag{11}$$

where, δ_0 the value of some initial air gap (Fig. 1). Expression (Eq. 11) completes Eq. 5-7 to the closed system by the number of equations as in this case, in Eq. 5-7 and 11 the number of independent variables and the number of equations becomes equal.

Replace variable x for δ in the Eq. 7 for the mechanical subsystem of a variable by Eq. 11, given that $-d\delta = dx$ and Eq. 10:

$$m_\Sigma \frac{d^2}{dt^2}\delta + R_{mech}\frac{d\delta}{dt} + \qquad (12)$$
$$K'_\Sigma\delta = K'_\Sigma\delta_0 - \frac{K_{stray}}{2\mu\mu_0 S_\Sigma}\Phi^2$$

Thus, it is possible to define the frame of reference in the mechanical subsystem makes relative to the air gap δ which is agreed with the definition of the value of the magnetic flux $\Phi_{(\delta)}$, so it is advisable to introduce the variable δ which is agreed with the definition of the value of the magnetic flux $\Phi_{(\delta)}$ and taking into account (Eq. 10) and the magnetic flux Φ. Therefore, it is advisable to insert the variable δ into the parameters of equations for the electrical subsystem (Eq. 5). Here, it is advisable to use some trick to simultaneously reduce the total number of equations in the system. Insert, using Eq. 10:

$$L = \frac{\Phi w}{i} = \frac{w^2}{\frac{k_{stray}\delta}{\mu_0 S_\mu}} = \frac{k}{\delta} \qquad (13)$$

Where:

$$k = \frac{w^2\mu_0 S_\mu}{k_{stray}}$$

L inductance of the electromagnetic coil and taking into account that:

$$\Phi = \frac{1}{w}Li = \frac{1}{w}k\frac{i}{\delta} \qquad (14)$$

Substitute Eq. 14 into 5, using Eq. 13, we obtain:

$$ri + \frac{k}{\delta}\times\frac{di}{dt} - i\frac{k}{\delta^2}\frac{d\delta}{dt} + \frac{1}{c}\int idt = U_{net} \qquad (15)$$

or identical expression relative to the magnetic flux Φ and the air gap δ:

$$\Phi\delta\frac{wr}{k} + w\frac{d\Phi}{dt} + \frac{w}{ck}\int(\Phi\delta)dt = U_{net} \qquad (16)$$

Thus, we obtain the following two types of systems of equations which can be considered mathematical models of the EME LFO. Based on Eq. 14 and 15 obtain:

$$\frac{k}{\delta}\times\frac{di}{dt} + i\left(r - \frac{k}{\delta^2}\times\frac{d\delta}{dt}\right) + \frac{1}{c}\int idt = U_{net}$$

$$m_\Sigma\frac{d^2\delta}{dt^2} + R_{mech}\frac{d\delta}{dt} + k'_\Sigma\delta = k'_\Sigma\delta_0 - \tilde{h}\left(\frac{i}{\delta}\right)^2 \qquad (17)$$

Where:

$$\tilde{h} = \frac{k_{stray}}{2\mu_0 S_\Sigma}\times\frac{k^2}{w^2}\times\frac{S_\mu^2 w^2\mu_0}{2S_\Sigma k_{stray}}$$

The resulting system of equations includes values of the current i and the air gap δ as unknowns. Therefore, it reflects the processes in mechanical and electrical subsystems explicitly. Since, according to at armature stationary vibrations in the EME LFO current i and the air gap δ can be represented in rows as conditional solutions of the system (Eq. 17), then the analysis of the functioning of the process hereinafter should refer specifically to this system of equations as a synchronizing communication in the parts with vibro effect in this case is implemented via the electric subsystem.

However, analysis of processes in a single EME have to refer to the factors, determining force action on the armature of an electromagnetic exciter of oscillations. In this case, it is advisable to use an explicit form of the magnetic subsystem factors, namely the value of magnetic flux. Then it is more convenient to form the mathematical model based on Eq. 12 and 16. Then we have:

$$\frac{wr}{k}\Phi\delta + w\frac{d\Phi}{dt} + \frac{w}{ck}\int\Phi\delta dt = U_{net} \qquad (18)$$

$$m_\Sigma\frac{d^2\delta}{dt^2} + R_{mech}\frac{d\delta}{dt} + \tilde{k}_\Sigma\delta = \tilde{k}_\Sigma\delta_0 - h\Phi^2 \qquad (19)$$

Note that this form of the mathematical model is the most informative for the analysis of processes in EME LFO to establish regularities in the distribution of harmonics Φ (t) according to (Komarov, 1974; Kuliev, 1981).

ANALYSIS OF ELECTROMAGNETIC EXCITER OF LOW FREQUENCIES IN SIMSCAPE ENVIRONMENT

Modeling and simulation of physical systems are implemented in Simscape which is a software tool of the MatlabR2013a environment.

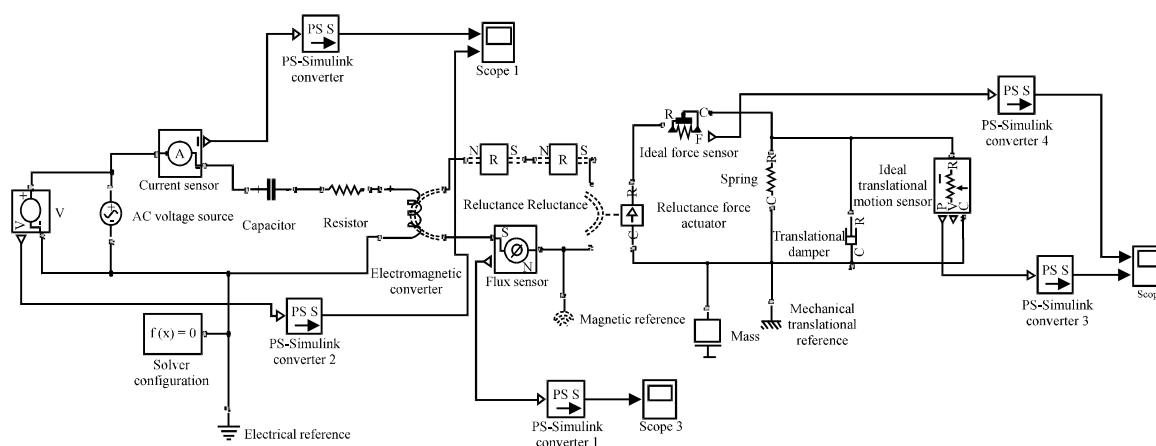Simscape contains components from different engineering areas: mechanical, electrical, magnetic,

Fig. 3: Physical model of the electromagnetic exciter of vibrational type

hydraulic and others. It provides the fundamental blocks for the construction of systems of these areas of knowledge. Simscape components use physical connections and models that match the structure of the system under development with preservation of all physical laws.

Therefore for the simulation of electromagnetic exciter of low frequencies Simscape was chosen. Based on the principle of operation (reciprocating motion due to the configuration of the resonance circuit) and the structure of the apparatus, there is detected the operation character with several types of energy conversion: electrical to magnetic and magnetic to mechanical. And, the main requirement to the developed model is the conservation of energy and power under the corresponding transformations.

According to the requirements was built a physical model of the electromagnetic exciter of vibrational type, shown in Fig. 3.

This model fully reflects the principle of operation and the physical processes occurring in the electromagnetic exciter. Due to a rich library there are all the basic components of Simscape and auxiliary tools of Simulink in place; connection between units of different instruments provided by a special compiler PS-S.

The model consists of three components: electrical, magnetic and mechanical. These parts in turn form their inherent circuits with their own physical elements.

For the formation of processes of transformation of electric energy into magnetic energy electromagnetic converter unit is used and to convert magnetic energy into mechanical reluctance force actuator unit is used.

Considering the operation of the apparatus from the electrical network as a source of electrical energy source was selected voltage source AC voltage source with predetermined amplitude parameters 220 sqrt (2) (V) and the frequency of 50 Hz. Electromagnetic converter unit in this circuit is a coil electromagnet in settings of which is

shown the number of turns (N = 1000) on the basis of this parameter the values of inductive resistance X_L and magnetic induction B are determined. Also, there is a presence of active resistance element (R = 10 ohms) in the circuit and a series capacitor (C = 10 mF) to form a resonance circuit.

The second circuit, connected with blocks electromagnetic converter and reluctance force actuator, is magnetic. Here, there are elements of magnetic resistance reluctance. Series connection of two magnetic resistances provokes an obstacle to the magnetic flux Φ depending on the given settings. The ratio of the Magnetomotive Force (MMF) through a component of the resulting flux that flows through the component is permanent and their ratio is determined by the magnetic resistance R.

The resistance depends on the geometry of the modeled section and is defined by the following relation:

$$R = g/(mu0 \times mur \times CSA) \qquad (20)$$

Where:
g   = The thickness of the section or air gap
mu0 = Constant permeability
mur = Relative permeance of the material
CSA = Sectional area

The first element of the magnetic resistance is the magnetic core (iron core) which has a thickness of 0.01 m, 0.01 m² sectional area and a relative magnetic permeance of 1,000. The second series element of the magnetic resistance is a fixed air gap with the following parameters: thickness of 0.001 m, sectional area of 0.01 m² and the relative magnetic permeance of 1.

To convert magnetic energy into mechanical energy is selected reluctance force actuator unit. When configuring this unit there were given two initial thickness of the air gap -2 mm, the minimum thickness (10^{-4}), the

cross sectional area of $0.15\,m^2$, relative permeance of 1, the coefficient of elasticity ($10^6\,N\,m^{-1}$), the dampening factor of 500 H/m/s. With this converter unit, the mechanical circuit is formed which is necessary to supplement with the elements, taking into account the reciprocating nature of the movement.

Given the operation principle of overcoming the stiffness force of the spring due to the resonance traction effort generated by the magnetic flux it is necessary to choose the appropriate elements of the mechanical circuit. For this purpose the units spring with stiffness of $1000\,N\,m^{-1}$) and translational damper with dampening coefficient of 20 N/m/s are chosen. These elements are connected in parallel in order to simulate the simultaneous effect of the spring stiffness and viscous friction in the mechanical reciprocating motion. To form the inertia element mass is added with the weight parameter of 1 kg.

After constructing the physical model with the appropriate parameters the problem arises of simulation and obtaining adequate results. This program allows to measure the processes with the introduction of additional measuring elements, depending on the option selected and the connection method.

The electromagnetic exciter of low frequencies model simulation duration was 3 sec. According to Fig. 3, at a resonance of the circuit due to the capacitor in 1 sec there is an increase in the current value for example, during the 2nd sec in which according to Fig. 4 there is an increase in traction effort. Thus, the periodicity of the resonant circuit determines the change in traction effort sinusoidally, based on which one can judge the reciprocating nature of the operation of the low frequencies' electromagnetic exciter. And, the change in the voltage amplitude of the voltage is not very noticeable (Fig. 4-7). Time characteristic of current in the electromagnetic exciter of low frequencies.
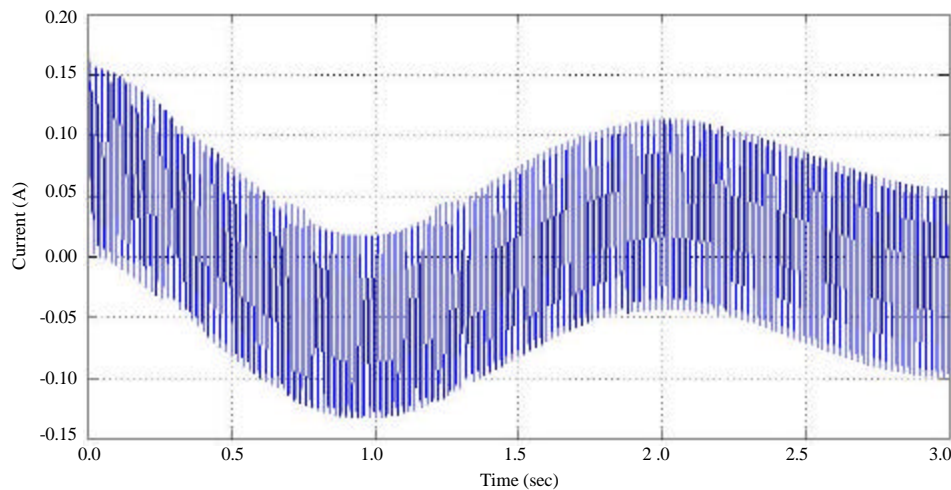

Fig. 4: Time characteristic of current in the electromagnetic exciter of low frequencies
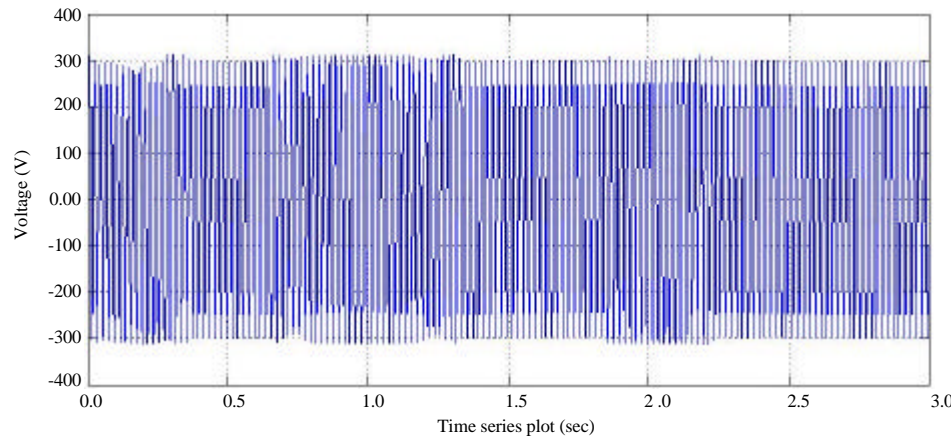

Fig. 5: Time characteristic of voltage in the electromagnetic exciter of low frequencies
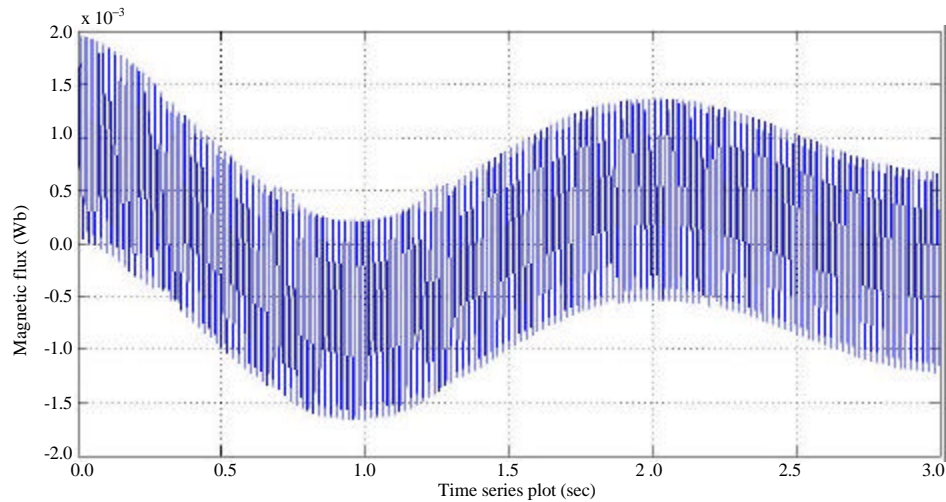
Fig. 6: Time characteristic of magnetic flux in the electromagnetic exciter of low frequencies
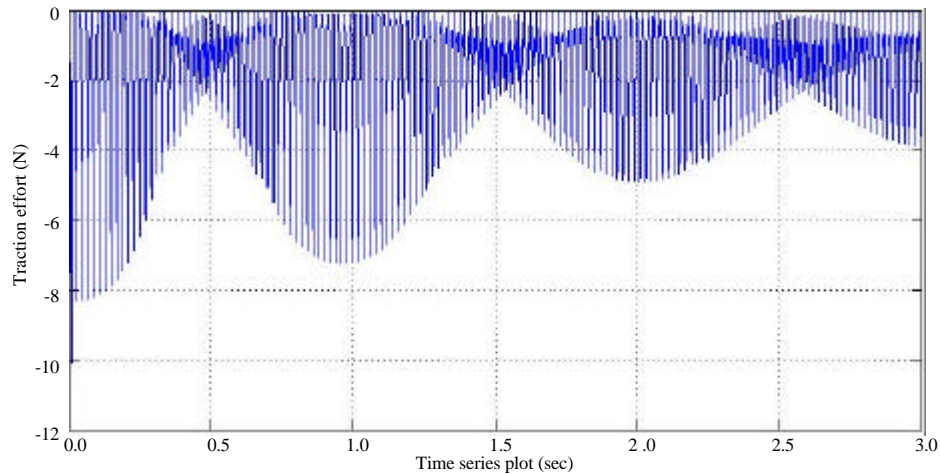

Fig. 7: Time characteristic of traction effort in the electromagnetic exciter of low frequencies

CONCLUSION

The rapid development of wireless communication technologies have made it as a vital tool in our daily life regardless of ages. So, studies in this area is very important. Based on the analytical comparison and review of processes in EME LFO in motor mode it is possible to formulate the following conclusion:

- The theoretical interpretation of the EME LFO functioning processes in generator mode is realizable and can be constructed based on the principle of reversibility of the electro-mechanical system
- From the standpoint of practical interpretation it is necessary to consider solution options including the model, allowing the realization of generator mode of the EME LFO functioning

In accordance with Fig. 8, we can see the electric circuit of vibration type electric generator. An anchor 2 of the mover mechanism 3 influence by source of a mechanical vibration with a constant amplitude and low mechanical frequency of fluctuations under the influence of which the anchor 2 will start making an oscillating motion concerning poles of a magnetic conductor 1 and the support. As a result in contours of windings 4 and $4^{/}$ in a magnetic conductor 1 there is a being summarized sinusoidal magnetic flux which induces in windings 4 and $4^{/}$ sinusoidal electromotive force with an invariable amplitude and the frequency corresponding to standard frequency of a network voltage. Standard frequency of output tension is provided by the block 7. Output clips of a magnetic conductor's windings are connected to an entrance of this block 4 and $4^{/}$, via consistently switched on capacitors 5 and $5^{/}$. To the exit clips can be connected the electric load.
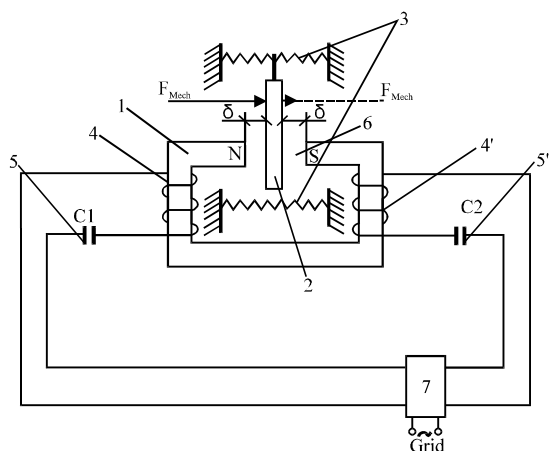
Fig. 8: The electric circuit of vibration type electric generator

The offered vibration type electric generator allows, thus, directly, without intermediate converting devices to transform low-frequency mechanical oscillating motions to alternating electric current of standard frequency. On this device the patent of the Republic of Kazakhstan is issued.

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